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Controlling High-Speed Instabilities in Semiconductor Lasers

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13. ABSTRACT *(Maximum 200 Words)*

We developed and characterized external-cavity semiconductor lasers as paradigms for complexity in optical systems. We measured precisely the properties of these lasers to elucidate the origin of low-dimensional chaotic behavior that occurs in these devices and developed models that accurately reflect the observed dynamics. Based on our findings, we developed and characterized high-speed techniques for controlling and synchronizing the laser dynamics.

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1. Controlling High-Speed Instabilities in Semiconductor Lasers

1.1. Statement of the Problem

The primary goal of our program is to investigate schemes for controlling and synchronizing semiconductor laser dynamics and to characterize chaos and instabilities occurring in such lasers. This work is important because semiconductor lasers and optical amplifiers are being considered for use in a variety of proposed military and civilian systems. Unfortunately, the power, coherence, modulation, and noise characteristics of individual laser diodes are not sufficient to meet the requirements of many of these proposed applications. We find that the nonlinear optical coupling in a semiconductor lasers can be exploited to overcome many of the limiting characteristics. We have performed an investigation that couples experimental and theoretical work on complicated laser structures to show how the nonlinear optical interactions influence the amplitude, phase, noise and modulation characteristics of the optical output and how these properties can be modified using small perturbations.

Specifically, we developed and characterized external-cavity semiconductor lasers as paradigms for complexity in optical systems. We measured precisely the properties of the semiconductor lasers to elucidate the origin of low-dimensional chaotic behavior that occurs in these devices and developed models that accurately reflect the observed dynamics. In addition, we conducted studies of the fundamental mechanisms for control and synchronization of fast dynamical systems and used these techniques to modify the laser characteristics. Finally, we have added significantly to the Human Resource Base of Ph.D.-level scientists who are trained in the nonlinear dynamical properties of lasers.

1.2. Summary of Important Results

1.2.1. Low-Frequency Fluctuations in Semiconductor Lasers

In the first phase of this part of our program, we developed an experimental set-up for investigating the dynamics of semiconductor lasers in the presence of external optical feedback. The set-up consists of a commercial semiconductor laser (SDL-5401-G1) mounted in mechanically and thermally stable environment, a variable-reflectivity external mirror whose spacing from the laser can be adjusted, extremely stable electronics for powering the laser and stabilizing its temperature, and high-speed detectors and recording devices for characterizing the laser dynamics. The electrical and mechanical assemblies were constructed in-house as part of this project.

During the next phase of this part of the program, we found that the laser exhibits an instability known as low-frequency fluctuations (LFF) when approximately 10% of the optical power reflected by the external mirror is injected into the laser and when the laser-mirror distance is adjusted to $\gtrsim$50 cm. It is believed that the laser in the LFF regime produces an erratic train of ultrashort pulses whose pulse width (in the range of 50-200 ps), spacing (200-1000 ps), and amplitude change form pulse to pulse. This pulsing behavior is interrupted at erratic intervals (50 ns-1 ms) by power drop out events where the average power suddenly drops, then gradually ($\sim$50 ns) builds up to its original value during chaotic itinerancy. While it is possible to predict the nature of the dropout events and its recovery to the high-power state in reasonable agreement with experimental observations, there is limited guidance regarding the statistics of the time intervals between power drop out events. Adding further to the complexity of the dynamics, recent observations suggest that spontaneous emission noise and multi-longitudinal-mode effects can alter significantly the time-interval statistics.

In an effort to understand origin of the long-time behavior of the power drop out events, we measured with high-resolution and -accuracy the time-interval distribution for our laser system under various experimental conditions. We compared our experimental measurements with the theoretical predictions of approximate analytic models of the laser dynamics. We find that our results are consistent with these models for some experimental conditions,

although our work indicates that new analytic treatments are necessary to capture precisely the long-term LFF dynamics. Our results were reported in a Rapid Communication appear in Physical Review A (Ref. 5, Sec. 2) and in Dr. Sukow's Ph.D. Dissertation (Ref. 7, Sec. 2).

We are also in the process of using the nonlinear analysis technique known as False Nearest Neighbors to determine the dimensionality of the attractor characterizing the power drop out events. Knowing the dimensionality of the system is important because it dictates the approach to controlling and synchronizing the LFF dynamics. If the system is low-dimensional, then standard control and synchronization techniques should be successful. Whereas new techniques will have to be developed if it is determined that the dynamics is high-dimensional. This analysis is not yet complete; we intend to complete the analysis and publish our findings after the end of the program.

1.2.2. Control of High-Speed Dynamical Systems

In this part of the program, we undertook a fundamental study of the issues related to controlling chaos and instabilities in fast dynamical system, with a special emphasis on the control of laser dynamics. In proof-of-concept experiments using chaotic electronic circuits, we identified methods for stabilizing unstable periodic orbits and unstable steady states. In addition, we performed a theoretical investigation for controlling the unstable steady states of lasers using these techniques.

Specifically, we stabilized unstable periodic orbits of a fast diode resonator driven at 10.1 MHz (corresponding to a drive period under 100 ns) using extended time-delay autosynchronization. Stabilization is achieved by feedback of an error signal that is proportional to the difference between the value of a state variable and an infinite series of values of the state variable delayed in time by integral multiples of the period of the orbit. The technique is easy to implement electronically and it has an all-optical counterpart that may be useful for stabilizing the dynamics of fast chaotic lasers. We show that increasing the weights given to temporally distant states enlarges the domain of control and reduces the sensitivity of the domain of control on the propagation delays in the feedback loop. We determine the average time to obtain control as a function of the feedback gain and identify the mechanisms that destabilize the system at the boundaries of the domain of control. A theoretical stability analysis of a model of the diode resonator in the presence of time-delay feedback is in good agreement with the experimental results for the size and shape of the domain of control. We were invited to present these results in a special issue of *Chaos* devoted to control and synchronization of dynamical systems (Ref. 6, Sec. 2).

We have also investigated techniques for controlling the dynamics of systems that are well described as a point process. Such a system evolves such that long periods of inactivity are punctuated by brief, nearly identical bursts of activity. The semiconductor laser in the LFF regime is approximately of this type, where the power drop out events are the brief bursts of activity. In a proof-of-concept experiment, we created a low-speed physical point process by passing a continuous, deterministic, chaotic signal through an integrate-and-fire device. The timing between the discrete events was controlled using proportional feedback incorporating only the time intervals between events. This system is unique in that the mean time between events can be adjusted independent of the dynamics of the underlying chaotic system. It is found that the range of feedback parameters giving rise to control as a function of the mean firing time exhibits surprisingly complex structure, and control is not possible when the mean interspike interval is comparable to or larger than the underlying system memory time. The results of this investigation will appear in a future issue of Physical Review E (Ref. 2, Sec. 2).

In addition, we investigated methods for stabilizing unstable states of chaotic systems using a variation of the extended time-delay autosynchronzation scheme described above. In a proof-of-concept experiment, we stabilized the unstable steady states of a low-speed chaotic electronic circuit by applying a feedback signal generated by high-pass-filtering in

real time the dynamical state of the system to an accessible system variable. The technique is easy to implement, does not require knowledge of the unstable steady state coordinates in phase space, automatically tracks changes in the system parameters, and is more robust to broadband noise than previous schemes. The simplicity and robustness of the scheme suggests that it is ideally suited for stabilizing unstable steady states in ultra-high-speed systems. The results of this investigation have been submitted recently to Chaos (Ref. 1, Sec. 2).

In light of the potential usefulness of this scheme, we conducted a theoretical study to assess whether specific implementations of the protocol might be applicable for stabilizing laser dynamics. Stabilizing the unstable steady states (continuous wave state) of laser is often desirable for applications because of the high degree of coherence of such states. For an idealized laser model, we found that there exists a wide range of feedback parameters giving rise to stable behavior (known as the *domain of control*) and the controller can automatically track slow variation or drift of the laser parameters. While it is well known that this idealized laser model does not describe quantitatively the behavior of typical lasers, these observations highlight the potential of the feedback schemes. Detail studies of specific laser systems must be undertaken to ascertain whether the controlling chaos techniques will be useful in real-world applications. The results of this study appeared recently in Optics Letters (Ref. 3, Sec. 2).

1.2.3. Synchronization of Dynamical Systems

While the control techniques described in the previous section may be useful for stabilizing the dynamics of single semiconductor lasers, a better approach for controlling the dynamics of arrays of lasers might involve control as well as synchronization techniques. To begin to explore the possibilities afforded by this method, we have undertaken a study of the fundamental mechanisms responsible for synchronization.

Surprisingly, we find that two coupled, nearly identical chaotic oscillators display incomplete synchronization over a wide range of coupling strengths and coupling schemes for which high-quality synchronization is expected. In this regime, long intervals of high-quality synchronization are interrupted at irregular times by large, brief desynchronization events, clearly demonstrating that the standard, widely used synchronization criterion is not always useful in experiments. The origin of these desynchronization events are a manifestation of a new type of dynamical behavior known as 'attractor bubbling' induced by slight noise or parameter mismatch. This behavior is generic to *all* synchronization schemes although its importance in a given situation depends on the detailed topological structure of the underlying attractors. One consequence of the occurrence of attractor bubbling is that it is not possible to predict the conditions under which a collection of chaotic systems will synchronize in a typical experimental situation since it is difficult, if not impossible, to predict the location of transition from high-quality synchronization to bubbling. We have determined that it is possible, however, to place an upper bound on the bubbling transition. The results of this research is described in Refs. 4, 8, and 10 in Sec. 2.

Our future plans are to continue these studies and attempt to identify a rigorous criterion for the synchronization of dynamical systems. The results of this program will be crucial for designing schemes for coherently locking the optical field generated by arrays of semiconductor lasers.

1.2.4. Controlling Low-Frequency Fluctuations in Semiconductor Lasers Using Small Perturbations

In this part of the program, we investigated whether it is possible to control the power drop out events of semiconductor lasers operating in the LFF regime. We determined that a high-speed electro-optic implementation of high-pass filter control, as described above and

in Refs. 1 and 3, Sec. 2, is not capable of stabilizing the laser dynamics. The scheme involved real time measurement of the intensity of the light generated by the laser using a high-speed photoreceiver, high-pass filtering of the electronic signal produced by the detector, and summing this signal with the current injected into the laser. Our preliminary conclusions are that control failed because of a variety of factors including: 1) the system is very high dimensional; 2) the injection current does not perturb the system in the correct direction in phase space; 3) the measured dynamical variable (the laser intensity) does not give sufficient information about the unstable directions in phase space; and 4) the control loop latency is too large.

In addition, we investigated the effects of applying a periodic modulation to the injection current of the semiconductor laser. It is found that very weak modulation ~~give~~ creates considerable structure in the probability distribution of the time interval between power drop out events when the modulation frequency is comparable to the relaxation oscillation frequency of the external cavity laser (~20 MHz for our set up). For strong modulation at this same frequency, it is possible to completely entrain the drop out events in that a drop out can be induced for every cycle of the periodic signal. However, we find that the periodic modulation has no effect on the LFF dynamics when the modulation frequency is equal to the longitudinal mode frequency of the external cavity (~212 MHz for our set up). Under no conditions do we find that it is possible to suppress the LFF instability using periodic modulation of the injection current. Our future plans are to prepare a manuscript describing our observations and submit it for publication in a peer-reviewed journal. The results of both of these studies is described in Ref. 7, Sec. 2.

2. List of Publications and Technical Reports

1. A. Chang, J.C. Bienfang, G.M. Hall, J.R. Gardner, and D.J. Gauthier, 'Stabilizing unstable steady states using extended time-delay autosynchronization,' submitted for publication to Chaos (1998).

2. G.M. Hall, S. Bahar, and D.J. Gauthier, 'Experimental control of a chaotic integrate-and-fire system using interspike intervals,' submitted for publication to Phys. Rev. E (1998).

3. D.J. Gauthier, 'Controlling lasers by use of extended time-delay autosynchronization,' Opt. Lett. **23**, 703 (1998).

4. D.J. Gauthier, 'Intermittent loss of synchronized chaos under conditions when high-quality synchronization is expected,' to appear in the Proceedings of the 4^{th} Experimental Chaos Conference (1997).

5. D.W. Sukow, J.R. Gardner, and D.J. Gauthier, 'Statisitics of power dropout events in semiconductor lasers with time-delayed optical feedback,' Phys. Rev. A (Rapid Communications) **56**, R3370 (1997).

6. D.W. Sukow, M.E. Bleich, D.J. Gauthier, and J.E.S. Socolar, 'Controlling chaos in fast dynamical systems: Experimental results and theoretical analysis,' Chaos **7**, 560 (1997).

7. D.W. Sukow, 'Experimental Control of Instabilities and Chaos in Fast Dynamical Systems,' Duke University Ph.D. Dissertation, unpublished.

8. S.C. Venkataramani, B.R. Hunt, E. Ott, D.J. Gauthier, and J.C. Bienfang, 'Bubbling transitions of chaotic systems,' Phys. Rev. Lett. **77**, 5361 (1996).

9. D.J. Gauthier and D.W. Sukow, 'Controlling chaos and instabilities in fast optical systems,' LEOS Newsletter **6**, 15 (1996).

10. D.J. Gauthier and J.C. Bienfang, 'Intermittent loss of synchronization in coupled chaotic oscillators: toward a new criterion for high-quality synchronization,' Phys. Rev. Lett. **77**, 1751 (1996).

3. List of Technical Presentations

* *denotes invited presentation*

1. * 'Linear and Nonlinear Chaos Control without Reference States,' Workshop on Theory, Diagnostics and Control of Chaos, December 5, 1997, Redstone Arsenal, Huntsville, AL.

2. * 'Controlling Chaos in Fast Optical Systems,' Southeastern Section of the American Physics Society Annual Meeting, November 6, 1997, Nashville, TN.

3. * 'Synchronization of Chaotic Systems,' 4th Experimental Chaos Conference, August 8, 1997, Boca Raton, FL.

4. * 'Dynamics and Control of High-Speed Instabilities and Chaos in Semiconductor Lasers,' Fundamentals and Modelling of Lasers and Ultra Short Pulse Interactions, University College, July 23, 1997, Cork, Ireland.

5. D.W. Sukow, 'Suppression and entrainment of power-dropout events in external-cavity semiconductor lasers,' Quantum Electronics and Laser Science Conference, May 22, 1997, Baltimore, MD.

6. * 'Controlling Chaos in Fast Optical Systems,' American Physics Society Annual March Meeting, March 21, 1997, Kansas City, MO.

7. D.W. Sukow,' Regulation of power-dropout events in an external Cavity Semiconductor Laser under Drive Current Modulation,' Dynamics Days Arizona, January 9, 1997, Scottsdale, AZ.

8. * 'Issues in controlling chaos in fast optical systems,' Workshop on Communication by Chaos: Digital Signal Generation by Simple Nonlinear Devices, U.S. Army Research Office, June 5, 1996, RTP, NC.

9. * 'Controlling chaos in fast optical systems,' 26^{th} Winter Colloquium on the Physics of Quantum Electronics, January 8, 1996, Snowbird, UT.

10. * 'Intermittent loss of synchronization in coupled dynamical systems,' Nonlinear Dyamics Seminar, December 14, 1995, Department of Physics, University of Maryland, College Park, MD.

11. * 'Intermittent loss of synchronization in coupled dynamical systems,' Nonlinear Dyamics Seminar, December 13, 1995, Naval Research Laboratory, Washington, DC.

12. * 'Controlling chaos in fast optical systems,' IEEE Lasers and Electro-Optics Society Washington/Northern Virginia Monthly Meeting, December 12, 1995, College Park, MD.

13. * 'Controlling chaos in fast optical systems,' IEEE Lasers and Electro-Optics Society Annual Meeting, October 30, 1995, San Francisco, CA.

14. 'Controlling the unstable steady-states of lasers using continuous feedback,' Conference on Nonlinear Dynamics in Optical Systems, June 7, 1995, Rochester, NY.

4. List of Participating Personnel

All personnel associated with this project are or were members of Prof. Daniel J. Gauthier's laboratory at the Duke University Department of Physics. The majority of the research for this contract was conducted by Dr. David W. Sukow, who is now a National Research Council Post-Doctoral Fellow at the Phillips Laboratory. In addition, Mr. Jonathan Blakely, Mr. Douglas Wick, Mr. Mark Steen, and Mr. Martin Hall, Graduate Research Assistants in Prof. Gauthier's Laboratory, were partially supported by and trained in the topical areas pertinent to this contract.

5. Inventions

No inventions have been disclosed as part of this grant.

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